

UNITED STATES PATENT APPLICATION

FOR

MULTI-FUNCTIONAL OPTICAL DEVICE UTILIZING MULTIPLE
POLARIZATION BEAM SPLITTERS AND NON-LINEAR INTERFEROMETERS

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MULTI-FUNCTIONAL OPTICAL DEVICE UTILIZING MULTIPLE POLARIZATION BEAM SPLITTERS AND NON-LINEAR INTERFEROMETERS

FIELD OF THE INVENTION

The present invention relates to fiber optic networks, and more particularly to wavelength division multiplexers, wavelength division de-multiplexers, optical isolators and optical circulators utilized in fiber optic networks carrying wavelength division multiplexed information signals.

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a Continuation-In-Part of co-pending U.S. Patent Application, titled "Multi-Functional Optical Device Utilizing Multiple Polarization Beam Splitters and Non-Linear Interferometers", Serial No. 09/630,891, filed on August 2, 2000.

BACKGROUND OF THE INVENTION

Fiber optic communication systems are becoming increasingly popular for data transmission due to their high speed and high data capacity capabilities. Wavelength division multiplexing is used in such fiber optic communication systems to transfer a relatively large amount of data at a high speed. In wavelength division multiplexing, multiple information-carrying signals, each signal comprising light of a specific restricted wavelength range, may be transmitted along the same optical fiber.

In this specification, these individual information-carrying lights are referred to as either "signals" or "channels." The totality of multiple combined signals in a wavelength-

division multiplexed optical fiber, optical line or optical system, wherein each signal is of a different wavelength range, is herein referred to as a "composite optical signal."

The term "wavelength," denoted by the Greek letter λ (lambda) is used herein synonymously with the terms "signal" or "channel." Although each information-carrying channel actually comprises light of a certain range of physical wavelengths, for simplicity, a single channel is referred to as a single wavelength, λ , and a plurality of n such channels are referred to as " n wavelengths" denoted λ_1 - λ_n . Used in this sense, the term "wavelength" may be understood to refer to "the channel nominally comprised of light of a range of physical wavelengths centered at the particular wavelength, λ ."

A crucial feature of fiber optic networks is the separation of the composite optical signal into its component wavelengths or channels, typically by a wavelength division demultiplexer. This separation must occur to allow for the exchange of signals between loops within optical communications networks. The exchange typically occurs at connector points, or points where two or more loops intersect for the purpose of exchanging wavelengths. Conventional methods utilized by wavelength division de-multiplexers in separating a composite optical signal into its component channels include the use of filters and fiber gratings as separators. A "separator" or "channel separator", as used in this specification, is an integrated collection of optical components functioning as a unit which separates one or more channels of a composite optical signal from one another, or else combines separate channels from separate inputs into a single composite optical signal.

A problem with the conventional separators is the precision required of a transmitter device—that is, a light emitting device which generates an optical signal at a particular wavelength—because of the narrow pass bands of such separators. This high precision is

difficult to accomplish. Further, signal transmitting devices must be aligned individually for each separator, which is time intensive. Still further, additional, separate optical isolator and optical circulator components must supplement the separators within the optical communications system, which is wasteful of space and resources. Also, there does not exist any single apparatus that combines the functionality of a channel separator with that of an isolator, a circulator, or a comb filter.

Accordingly, there exists a need for a multi-functional separator which is easily aligned. The multi-functional separator should be able to incorporate additional isolator, circulator and comb-filter functionalities. The present invention addresses such a need.

SUMMARY OF THE INVENTION

The present invention provides a multi-functional optical channel separator that may be used as a demultiplexer, a multiplexer or an Add/Drop Multiplexer in wavelength division multiplexed optical communication systems. The preferred embodiment of the multi-functional separator comprises a first, a second and a third polarization beam splitter (PBS), a first set of optical rotators comprising a first non-reciprocal optical rotator (NRR) and a first reciprocal optical rotator (RR) optically coupled between the first and second PBS's, a second set of optical rotators comprising a second NRR and a second RR optically coupled between the second and third PBS's and a first, second and third reflective non-linear interferometer (NLI), or reflection interferometer (RI). Within this preferred embodiment, the first NLI is optically coupled to the second PBS, the second NLI is optically coupled to the first PBS and the third NLI is optically coupled to the third PBS, wherein the first and second PBS's and the first set of optical rotators lie along a first axis,

the second and third PBS's and the first and second NLI's lie along a second axis not parallel to the first axis, and the first PBS and second NLI lie along a third axis not parallel to first axis. Preferably, the preferred embodiment of the present invention is an Optical Add/Drop Multiplexer and may further comprise an Input Port optically coupled to the first PBS and lying along the first axis, a Drop Port optically coupled to the first PBS and lying along the third axis, an Output Port optically coupled to the second PBS and lying along the first axis, and an Add Port optically coupled to the third PBS.

BRIEF DESCRIPTION OF THE FIGURES

Figures 1a-1c illustrate a first preferred embodiment of a multi-functional separator in accordance with the present invention.

Figure 1d illustrates in more detail the structure of a polarizing port which is utilized either for input or output in the first preferred embodiment of the multi-functional separator in accordance with the present invention.

Figure 1e illustrates a second preferred embodiment of a multi-functional separator in accordance with the present invention.

Figure 1f illustrates a detailed perspective view of light polarization rotation upon propagation through a non-reciprocal optical rotation element together with a reciprocal optical rotation element.

Figures 2a-2b illustrate a third preferred embodiment of a multi-functional separator in accordance with the present invention.

Figures 3a-3b illustrate a fourth preferred embodiment of a multi-functional separator in accordance with the present invention.

Figures 4a-4c illustrate a fifth preferred embodiment of a multi-functional separator

in accordance with the present invention.

Figures 5a-5c illustrate side views of a sixth preferred embodiment of a multi-functional separator in accordance with the present invention.

Figures 6a-6f illustrate a seventh preferred embodiment of a multi-functional separator in accordance with the present invention.

Figure 6g illustrates a side view of an eighth preferred embodiment of a multi-functional separator in accordance with the present invention.

Figure 6h illustrates a side view of a ninth preferred embodiment of a multi-functional separator in accordance with the present invention.

Figures 7a-7e illustrate a tenth preferred embodiment of a multi-functional separator in accordance with the present invention.

Figure 7f presents a side view of an eleventh preferred embodiment of a multi-functional separator in accordance with the present invention.

Figure 8 illustrates a twelfth preferred embodiment of a multi-functional separator in accordance with the present invention.

Figure 9A is a side view of a first preferred embodiment of an interleaved Optical Add/Drop Multiplexer (interleaved OADM) in accordance with the present invention showing the forward pathways of signal light rays of even and odd channels therethrough after being input from an Input Port.

Figure 9B is a side view of the interleaved OADM of Fig. 9A showing the return pathways therethrough of signal light rays of odd channels to a Drop Port and of even channels to an Output Port.

Figure 9C is a side view of the interleaved OADM of Fig. 9A showing the pathway therethrough of signal light rays of odd channels from an Add Port to the Output Port.

Figure 9D is a side view of the interleaved OADM of Fig. 9A showing the pathway therethrough of misdirected light rays of even channels.

5 Figure 9E is a side view of the interleaved OADM of Fig. 9A showing the pathway therethrough of misdirected light rays of odd channels.

Figure 10A is a side view of a second preferred embodiment of an interleaved OADM in accordance with an embodiment of the present invention showing the return pathways therethrough of signal light rays of odd channels to a Drop Port and of even channels to an Output Port.

Figure 10B is a side view of a third preferred embodiment of an interleaved OADM in accordance with an embodiment of the present invention showing the return pathways therethrough of signal light rays of odd channels to a Drop Port and of even channels to an Output Port.

15 Figure 11 is a functional signal routing diagram of an interleaved OADM apparatus in accordance with the present invention.

DETAILED DESCRIPTION

20 The present invention provides a multi-functional channel separator and channel combiner which is easily aligned. The following description is presented to enable one of ordinary skill in the art to make and use the invention and is provided in the context of a patent application and its requirements. Various modifications to the preferred embodiment will be readily apparent to those skilled in the art and the generic principles herein may be

applied to other embodiments. Thus, the present invention is not intended to be limited to the embodiment shown but is to be accorded the widest scope consistent with the principles and features described herein.

To more particularly describe the features of the present invention, please refer to Figures 1 through 11 in conjunction with the discussion below.

Figure 1a illustrates a first preferred embodiment of a multi-functional separator in accordance with the present invention. The first preferred embodiment provides a 1x2 channel separator 100. As will become apparent from the following discussion, the channel separator 100 receives input from a first optical port 116a and separates the channels therein into a first set of channels and a second set of channels that are output from a first output optical port 116b and a second output optical port 116c, respectively. The optical ports 116a-116c are also referred to herein as polarizing ports. The separator 100 comprises a first 102 and a second 104 polarization beam splitter (PBS) between which are disposed a non-reciprocal optical rotation element 106 and a reciprocal optical rotation element 108. The first PBS 102 receives optical input from the input port 116a which is disposed adjacent to a side of the PBS 102 opposite to the non-reciprocal rotator 106 and reciprocal rotator 108. A non-linear interferometer 110 is disposed adjacent to the second PBS 104 at a side opposite to the non-reciprocal rotator 106 and reciprocal rotator 108. The input port 116a, first PBS 102, second PBS 104, non-reciprocal rotator 106, reciprocal rotator 108 and non-linear interferometer 110 are disposed along a line which defines a main axis or dimension of the channel separator 100.

Also shown in Fig. 1a, as well as in several following figures of this specification, are the polarization orientations of various signal light rays. These polarization orientations

are indicated by double barbed arrows and/or crosses inscribed within circles. Unless otherwise indicated, double barbed arrows indicate light polarization along the indicated direction within the plane of the illustration, and crosses indicate light polarization normal to the plane of the page. Superimposed arrows and crosses either indicate non-polarized or randomly polarized light or superimposed rays which, in projection, have mutually perpendicular polarization plane orientations.

As shown in the side view of Fig. 1a, a first 112 and a second 114 optical reflector are disposed adjacent to respective faces of the first PBS 102 and second PBS 104, neither of which faces intersect the main axis of the separator 100. The optical reflectors 112-114 comprise right-angle prisms, but could also comprise mirrors. The two PBS's 102-104 each have the property of transmitting signal light comprising a first polarization (p-polarization) therethrough along the main axis whilst simultaneously deflecting signal light comprising a second polarization (s-polarization) to the adjacent optical reflector. Finally, the first output port 116b and the second output port 116c are disposed such that they receive light deflected by the first 112 and second 114 optical reflector, respectively.

Figure 1d illustrates in more detail the structure of a polarizing port 116, which is utilized either for input or output in the first preferred embodiment of the multi-functional separator in accordance with the present invention. The port 116 is herein termed a "polarizing port" because the port outputs light comprising only a single linear polarization orientation and can only receive light comprising the same linear polarization orientation. Unless otherwise specified, all references to "ports" within this specification are to be understood as referring to polarizing ports of the type illustrated in Fig. 1d. The polarizing port 116 comprises an optical fiber 180, an optical collimator 182, a birefringent walk-off

plate 184 and a reciprocal optical rotator 186. The optical collimator 182 is optically coupled to the optical fiber 180 and either receives input from or directs output to the fiber 180. When the optical fiber 180 is utilized to deliver input light, the collimator 182 receives diverging light rays and sets these rays parallel to one another so as to form a light beam.

5 When the optical fiber 180 receives output light, the collimator 182 focuses a beam of collimated light into the end face of the fiber 180.

The birefringent walk-off plate 184 of the polarizing port 116 (Fig. 1d) is optically coupled to the collimator 182 at a side opposite to the fiber 180 and has the property of physically separating an unpolarized light beam received from collimator 182 into a deflected light beam 190 and an un-deflected light beam 188. The deflected light 190 comprises an e-ray having a first linear polarization orientation and the un-deflected light 188 comprises an o-ray having a second linear polarization orientation perpendicular to that of the e-ray.

Immediately after passing through the birefringent walk-off plate 184 of the polarizing port 116 (Fig. 1d), the two beams 188-190 emerge parallel to one another but have mutually orthogonal polarization orientations. The reciprocal optical rotator 186, which is optically coupled to the birefringent walk-off plate 184 at a side opposite to the collimator 182, is disposed so as to intercept the path of only one of the two beams 188-190.

The reciprocal optical rotator 186 rotates the polarization orientation of said intercepted beam by 90° so as to be parallel to that of the other beam. In the reverse light propagation direction, that is, when the polarizing port 116 is utilized as an output port, the optical rotator 186 rotates the polarization orientation of only one of two beams so that the beams subsequently comprise mutually orthogonal polarization orientations and such that these two

beams are subsequently combined upon passage through the birefringent walk-off plate 184.

The reciprocal optical rotator 186 may be disposed so as to intercept either the o-ray 188 or the e-ray 190.

Referring once again to Fig. 1a, the pathways and polarization orientations of forward propagating input signal rays are shown in both top view (top diagram) and side view (lower diagram). The full set of two input beams, as separated by input port 116a, is only visible in the top view. Signal light, which is comprised of a plurality of wavelength division multiplexed channels λ_1 - λ_n is input to the first PBS 102 of channel separator 100 through input port 116a such that the two separated input beams both comprise p-polarization with respect to the first PBS 102. These two p-polarized signal light beams both pass straight through the PBS 102 and subsequently pass through the combination of the non-reciprocal optical rotator 106 and the reciprocal optical rotator 108. The elements 106-108 are disposed such that light passing through both from left to right does not experience polarization plane rotation. Thus, the signal light remains p-polarized with respect to the second PBS 104 and passes directly therethrough so as to be input to the non-linear interferometer 110. The non-linear interferometer 110 is disclosed in a United States Patents Nos. 6,169,604, and 6,310,690, both assigned to the assignee of the present application. These patents are incorporated herein by reference in their entirety.

Figures 1b and 1c illustrate the return pathways (that is, the pathways after reflection from and interaction with the non-linear interferometer 110) of odd and even channels, respectively, through the first preferred embodiment of the multi-functional separator 100 in accordance with the present invention. The non-linear interferometer 110 has the property of reflecting all linearly polarized light input thereto such that reflected light comprising a

first set of channels (e.g., the “odd” channels) that is interleaved with a second set of channels is reflected without any polarization plane rotation whereas the reflected light comprising the second set of channels (e.g., the “even” channels) is reflected with a 90° polarization plane rotation. Thus, as illustrated in the lower diagram of Fig. 1b, the light of the reflected odd channels, whose polarization is not rotated, remains p-polarized with respect to the second PBS 104 and therefore passes without deflection directly through the PBS 104 towards the reciprocal optical rotator 108 and non-reciprocal optical rotator 106. Contrariwise, as illustrated in the lower diagram of Fig. 1c, the light of the reflected even channels, whose polarization plane is rotated by 90° upon reflection from non-linear interferometer 110, is s-polarized with respect to the second PBS 104 and therefore is deflected towards the second optical reflector 114.

During passage from right-to-left through the pair of elements 106-108, the polarization plane orientation of the light of the odd channels (Fig. 1b) is rotated by 90° and thus acquires s-polarization with respect to the first PBS 102. The first PBS 102 therefore deflects this light comprising the odd channels towards the first optical reflector 112. Thus, as illustrated in Fig. 1b and Fig. 1c, the odd channels are deflected by first reflector 112 so as to be output to the first output port 116b whereas the even channels are simultaneously deflected by second reflector 114 so as to be output to the second output port 116c. As described previously, the two physically separate beams comprising each set of output channels are recombined by each respective output port and focused into the respective fiber of said port. In this fashion the separator 100 behaves as a wavelength division demultiplexer.

As illustrated in Fig. 1b, it is possible that a small, unwanted proportion 118 of s-polarized signal light may pass straight through the PBS 102 in the direction of port 116a as a result of imperfect separation of polarized light by PBS 102 and/or PBS 104. However, this small, unwanted proportion 118 of light is effectively prevented from being output from channel separator 100 through the port 116a as a result of the fact that the small proportion 118 is polarized perpendicularly to the polarization orientation than can be received by port 116a.

Figure 1e illustrates a second preferred embodiment of a multi-functional separator in accordance with the present invention. The second preferred embodiment provides a 1x2 channel separator 150. The channel separator 150 is constructed and operates similarly to the channel separator 100 (Figs. 1a-1c) except that the optical reflectors 112-114 of channel separator 100 are removed and the output ports 116b and 116c are disposed adjacent to the polarization beam splitters 102 and 104, respectively. The channel separator 150 has the advantage, over separator 100 (Figs. 1a-1c) of fewer optical components. Other aspects of the operation of channel separator 150 are similar to those of channel separator 100 and are not repeated. Many other similar modifications, in which the beam direction is modified, folded or unfolded as the result of insertion or removal of a simple beam reflection or offset element, would be readily apparent to one of ordinary skill in the art. All such modifications to any of the described embodiments of the present invention are considered to be within the spirit and scope of the present invention.

Figure 1f illustrates a detailed perspective view of light polarization rotation upon propagation through a non-reciprocal optical rotation element together with a reciprocal optical rotation element. In particular, Fig. 1f illustrates one possible configuration in which

the non-reciprocal optical rotator 106 comprises a Faraday rotator that rotates the polarization plane of linearly polarized light by 45° counter clockwise (as viewed from the left side of the apparatus) and the reciprocal optical rotator 108 comprises a half-wave plate with its optical axis disposed at 22.5° to the vertical. Other configurations are also possible and the invention is not meant to be limited to the particular disposition of these two components shown in Fig. 1f.

The 45 degree Faraday rotation element (Fig. 1f), which is well-known in the art, is typically comprised of a ferromagnetic oxide crystal such as yttrium iron garnet (YIG) or else of a diamagnetic glass with a high lead oxide content, or a paramagnetic glass or cubic crystal containing various ions such as trivalent cerium or terbium. The optical rotation of the Faraday rotator typically occurs in response to an externally applied axial magnetic field provided by adjacent permanent magnets or an electro-magnet (not shown). In Fig. 1f, double-barbed arrows inscribed within circles represent the orientations of linearly polarized light as viewed from the left side of the pair of components. Two possible polarization orientations are shown inscribed within each circle, wherein one such polarization orientation is indicated by a dashed arrow for ease of reference. The non-reciprocal optical rotator 106 always rotates the polarization plane of light passing therethrough in either direction by 45° counter clockwise (as viewed from the left side of the apparatus) and, for the illustrated polarization orientations, the reciprocal optical rotator 108 always rotates the polarization plane of light passing therethrough by 45° clockwise (as viewed from the side at which the light enters the rotator 108). By tracing the polarization orientations in either direction through the two optical rotators, it can be seen that the net polarization plane

rotation is zero for light propagating from left to right through both rotators 106-108 and is 90° for light propagating from right to left through both rotators.

Figures 2a-2b illustrate a third preferred embodiment of a multi-functional separator in accordance with the present invention. The third preferred embodiment provides a 1x2
5 dense wavelength division de-multiplexer and an optical isolator. The channel separator 200 illustrated in Figs. 2a-2b comprises all the components and functionality previously described in reference to the channel separator 100 (Figs. 1a-1c). Therefore the common components are shown with similar reference numbers to those in channel separator 100 and the common functionality is not re-described. However, the channel separator 200
10 comprises an extra non-reciprocal optical rotator 202 and a reciprocal optical rotator 204 disposed between the second PBS 104 and the second optical reflector 114 as shown in Figs. 2a-2b. The pair of components 202-204 comprises the property such that linearly polarized light passing completely therethrough from top to bottom does not experience polarization plane rotation whereas linearly polarized light passing completely therethrough from bottom
15 to top incurs a 90°-polarization plane rotation.

The channel separator 200 (Figs. 2a-2b) comprises an additional optical isolator functionality relative to the channel separator 100 (Figs. 1a-1c). Thus, signal light inadvertently input to the channel separator 200 from one or the other of the output ports 116b-116c as a result of reflections from optical surfaces or light back scattering is
20 prevented from returning to the input port 116a. Figures 2a and 2b respectively illustrate the pathways through channel separator 200 of light input to the separator from the second output port 116c and from the first output port 116b.

As shown in either Fig. 2a or Fig. 2b, light input from either of the output ports 116b-116c is polarized perpendicularly to the plane of the respective diagram as a result of the polarization functionality of said ports. Light input from second output port 116c comprises s-polarization with respect to the second optical reflector 114 and is deflected by the optical reflector towards and through the reciprocal optical rotator 204 and the non-reciprocal optical rotator 202 to the second PBS 104. The pair of components 202-204 comprises the property such that linearly polarized light passing completely therethrough from bottom to top incurs a 90° polarization plane rotation and thus the signal light from port 116c is transformed to p-polarization with respect to the second PBS 104. As shown in Fig. 2a, this p-polarized light passes completely through the second PBS 104 so as to exit the apparatus without being directed towards the input port 116a.

As illustrated in Fig. 2b, light input from the first output port 116b to channel separator 200 comprises s-polarization with respect to the first optical reflector 112 and the first PBS 102. This light is thus deflected by both the optical reflector 112 and the first PBS 102 towards and through the non-reciprocal optical rotator 106 and the reciprocal optical rotator 108 to the second PBS 104. The pair of components 106-108 comprises the property such that linearly polarized light passing completely therethrough from left to right does not incur polarization plane rotation and thus the signal light from port 116b remains s-polarized with respect to the second PBS 104. As shown in Fig. 2b, the second PBS 104 reflects this s-polarized light so as to exit the channel separator 200 without being directed towards the input port 116a. In this fashion, the channel separator 200 performs as an optical isolator.

Figure 3a illustrates a fourth preferred embodiment of a multi-functional separator in accordance with the present invention. The fourth preferred embodiment provides a 1x2

dense wavelength division de-multiplexer and an optical circulator. Figure 3a illustrates a side view of the separator/circulator 300. The separator/circulator comprises all the components of channel separator 200 (Fig. 2a) together with one additional component—an additional output port 302. The output port 302 does not comprise a polarizing port of the type illustrated in Fig. 1d and may be a conventional optical port comprising a collimating lens optically coupled to an optical fiber. The components common to channel separator 200 and separator/circulator 300 are numbered similarly in Figs. 2a, 2b and 3a. Further, the odd/even channel separation functionality of separator/circulator 300 is similar to that of channel separator 100 (Figs. 1a-1c) and that of channel separator 200 (Figs. 2a-2b) and is not re-described here. Further, the pathways of light input from ports 116b-116c to and through the separator/circulator 300 are identical to those already described for channel separator 200 (Figs. 2a-2b) except that, upon exit from the separator/circulator 300, the light is output to the output port 302. Because superimposed light beams comprising two polarizations are delivered to the output port 302, this port 302 comprises a simple collimator and optical fiber and does not comprise an optical rotator or birefringent walk-off plate. The apparent spatial offset between the two beams delivered to port 302 shown in Fig. 3a is provided for illustration purposes only, and is not real. In fact, the two beams delivered into the output port 302 are superimposed one upon the other.

Figure 3b illustrates the signal routing performed by the fourth preferred embodiment of the multi-functional separator in accordance with the present invention. In the separator/circulator 300, as shown in Fig. 3b, the port 116a comprises an input port, the port 302 comprises an output port and the ports 116b-116c comprise ports utilized for both input and output. Light comprising a plurality of wavelength division multiplexed channels λ_1 - λ_n

input to separator/circulator 300 through input port 116a is separated into two sets of channels—a set of “odd” channels $\lambda_1, \lambda_3, \lambda_5, \dots$ which is directed to and output from the input/output port 116b and a set of “even” channels $\lambda_2, \lambda_4, \lambda_6, \dots$ which is directed to and output from the input/output port 116c—by separator/circulator 300. Simultaneously with or alternatively to this channel separation, channels may be input to the separator/circulator 300 through one or both of the input/output ports 116b-116c. Such channels, input from either port 116b or 116c, are not directed to port 116a but are instead directed to output port 302 so as to be output from the separator/circulator 300. In this fashion, the separator/circulator 300 simultaneously functions as both a channel separator and as a pair of three-port optical circulators—one circulator (dashed lines in Fig. 3b) for odd channels and a second circulator (solid lines in Fig. 3b) for even channels.

Figures 4a-4c illustrate a fifth preferred embodiment of a multi-functional separator in accordance with the present invention. The fifth preferred embodiment provides a 2×1 dense wavelength division multiplexer as well as an optical isolator. The multiplexer 400 (Figs. 4a-4c) is identical in construction to the channel separator 200 (Figs. 2a-2b) except that each adjacent pair of optical rotators functions in the reverse sense from the corresponding pair of rotators in the channel separator 200. For example, in the multiplexer 400, the pair of optical rotators 106-108 rotates by 90° the polarization plane of light propagating therethrough from left to right, instead of from right to left as in channel separator 200. This reverse-sense operation also applies for the pair of optical rotators 202-204. In this specification, a drafting convention is adopted such that the polarization orientation of linearly polarized light is rotated by 90° upon passing through a reciprocal and a non-reciprocal optical rotator in sequence but experiences no net rotation upon passing

through a non-reciprocal and a reciprocal optical rotator in sequence. Thus, in Figs. 4a-4c, the reverse-sense operation of the pair of optical rotators is illustrated by simple interchange of the positions of the two optical rotators within each pair of rotators 106-108 and 202-204.

However, one of ordinary skill in the art will readily envision many alternative means of accomplishing the forward-sense and the reverse-sense operations of the optical rotators. Neither the multiplexers nor the demultiplexers in accordance with the present invention need be limited to any particular sequence of optical rotators within a pair of adjacent optical rotators.

In the multiplexer 400 (Figs. 4a-4b), the ports 116b and 116c serve to input signal light comprising odd channels and even channels, respectively, to the apparatus 400 and the port 116a serves to output signal light from the multiplexer 400. Because of the disposition of the rotators 106-108 in multiplexer 400, linearly polarized light passing completely through the pair of rotators 106-108 from right to left does not experience polarization plane rotation whereas linearly polarized light passing completely therethrough from left to right incurs a 90°-polarization plane rotation. Further, because of the disposition of the rotators 202-204 in multiplexer 400, linearly polarized light passing completely through the pair of rotators from bottom to top does not experience polarization plane rotation whereas linearly polarized light passing completely therethrough from top to bottom incurs a 90°-polarization plane rotation.

Figure 4a illustrates the forward pathways—that is, pathways up to the non-linear interferometer 110—of signal light rays of both even and odd channels through the multiplexer 400. Light that is input to multiplexer 400 from either of the ports 116b-116c is polarized perpendicularly to the plane of the figure as a result of the polarization

functionality of the ports. Light input to multiplexer 400 from port 116c comprises s-polarization with respect to the second optical reflector 114 and is deflected by the optical reflector 114 towards and through the non-reciprocal optical rotator 202 and the reciprocal optical rotator 204 to the second PBS 104. Because the polarization plane of the linearly polarized signal light comprising the even channels is not rotated upon passing through rotators 202-204 from bottom to top, this signal light remains s-polarized with respect to the second PBS 104 and is reflected towards the non-linear interferometer 110. Light that is input to multiplexer 400 from the port 116b comprises s-polarization with respect to the first optical reflector 112 and the first PBS 102. This light is thus deflected by both the optical reflector 112 and the first PBS 102 towards and through the reciprocal optical rotator 108 and the non-reciprocal optical rotator 106 to the second PBS 104. Because the polarization plane of the linearly polarized signal light comprising the odd channels is rotated by 90° upon passing through rotators 106-108 from left to right, this signal light is transformed to p-polarized light with respect to the second PBS 104 and is thus transmitted through PBS 104 towards the non-linear interferometer 110.

Figure 4b illustrates the return pathways—that is, pathways subsequent to reflection from the non-linear interferometer 110—of signal light rays of odd channels and even channels through the fifth preferred embodiment of the multi-functional separator in accordance with the present invention. Upon interaction with and reflection from the non-linear interferometer 110 the polarization plane of the signal light comprising the even channels is rotated so as to become vertically polarized whilst the polarization plane of the signal light comprising the odd channels remains vertically polarized. Therefore, as shown in Fig. 4b, the combined light comprising the odd and the even channels is reflected from

non-linear interferometer 110 with vertical polarization. This vertically polarized light comprises p-polarization with respect to the second PBS 104 and thus passes completely through the second PBS 104 towards and through the non-reciprocal optical rotator 106 and the reciprocal optical rotator 108. In the multiplexer 400, the pair of components 106-108 comprises the property such that linearly polarized light passing completely therethrough from right to left does not incur polarization plane rotation and thus the returning signal light remains p-polarized with respect to the first PBS 102. As shown in Fig. 4b, this p-polarized combined signal light of odd and even channels is transmitted completely through the first PBS 102 so as to be output from the multiplexer 400 through the port 116a. In this fashion, the apparatus 400 performs as a multiplexer, such that odd channels input from port 116b and even channels input from port 116c are all output from the single port 116a.

Figure 4c illustrates the optical isolator functionality of the fifth preferred embodiment of the multi-functional separator in accordance with the present invention. Fig. 4c illustrates the pathways through the multiplexer 400 of signal light rays inadvertently input to the apparatus from port 116a. As shown in Fig. 4c, such light rays are delivered from port 116a with vertical polarization. Since this vertical polarization comprises p-polarization with respect to the first PBS 102, this inadvertently input signal light passes completely through the first PBS 102 to and through the pair of optical rotators 106-108. In the multiplexer 400, the pair of optical rotators 106-108 comprises the property such that linearly polarized light passing completely therethrough from left to right incurs a 90°-polarization plane rotation. Therefore, upon passing through the pair of optical rotators 106-108, the inadvertently input signal light is transformed to s-polarized light with respect to the second PBS 104. As shown in Fig. 4c, the second PBS 104 reflects this s-polarized light so

as to exit the multiplexer 400 without entering either of the ports 116b-116c. In this fashion, the multiplexer 400 performs as an optical isolator.

Figures 5a-5c illustrate side views of a sixth preferred embodiment of a multi-functional separator in accordance with the present invention. The sixth preferred embodiment provides a 2x2 dense wavelength division multiplexer and an optical isolator. In the channel separator 500, the three ports 116a-116c, first PBS 102, non-reciprocal optical rotator 106, reciprocal optical rotator 108, non-reciprocal optical rotator 202, reciprocal optical rotator 204, second PBS 104, non-linear interferometer 110 and optical reflector 112 are common to and disposed similarly to the respective similarly numbered components in the channel separator 200 (Figs. 2a-2b) and the separator/circulator 300 (Fig. 3a). However, in the channel separator 500, a third PBS 502 replaces the optical reflector 114 (Figs. 2a, 3a) and an additional input port 116d is optically coupled to and disposed adjacent to a face of the third PBS 502.

The functionality of the channel separator 500 with respect to a plurality of channels λ_1 - λ_n input to the channel separator 500 from input port 116a is similar to that of the channel separator 100 and the channel separator 200 and already described in reference to Figs. 1a-1c. Thus, according to the prior discussion, the channels λ_1 - λ_n are separated into a first set of channels (e.g., “odd” channels $\lambda_1, \lambda_3, \lambda_5, \dots$) that are output from the channel separator 500 via port 116b and a second set of channels interleaved with the first set (e.g., “even” channels $\lambda_2, \lambda_4, \lambda_6, \dots$) that are output from the channel separator 500 via port 116c.

The channel separator 500 (Figs. 5a-5b) comprises additional functionality beyond that of the channel separators 100 and 200 with respect to the routing of a plurality of channels λ'_1 - λ'_n that are input to the channel separator 500 from the second input port 116d.

It is to be understood that, although the wavelengths of the channels λ'_1 - λ'_n are identical to those of the respective channels λ_1 - λ_n input via port 116a, the signals differ between the two sets of channels. The pathways of the odd channels $\lambda'_1, \lambda'_3, \lambda'_5, \dots$ and of the even channels $\lambda'_2, \lambda'_4, \lambda'_6, \dots$ through the channel separator 500 are illustrated in Figs. 5a and 5b, respectively. The input port 116d is disposed such that the light of all channels λ'_1 - λ'_n is directed towards the third PBS 502 and comprises a polarization orientation corresponding to p-polarization with respect to PBS 502. The p-polarized channels λ'_1 - λ'_n thus pass directly through the PBS 502 and are directed towards and through the reciprocal optical rotator 204 and the non-reciprocal optical rotator 202 and thence towards the second PBS 104. The pair of components 202-204 comprises the property such that linearly polarized light passing completely therethrough from bottom to top incurs a 90° polarization plane rotation. Therefore, the signal light from port 116d is rotated and transformed to s-polarization with respect to the second PBS 104. The s-polarized signals λ'_1 - λ'_n are thus reflected by the second PBS 104 and directed to the non-linear interferometer 110.

As described previously, the non-linear interferometer 110 has the property of reflecting all light input thereto such that reflected light comprising the “odd” channels is reflected therefrom without any polarization plane rotation whereas the reflected light comprising the “even” channels is reflected with a 90° polarization plane rotation. Thus, as illustrated in Fig. 5a, the light of the reflected odd channels $\lambda'_1, \lambda'_3, \lambda'_5, \dots$ whose polarization is not rotated, remains s-polarized with respect to the second PBS 104 and therefore is reflected by the PBS 104 towards and through the non-reciprocal optical rotator 202 and the reciprocal optical rotator 204. Contrariwise, as illustrated Fig. 5b, the light of the reflected even channels $\lambda'_2, \lambda'_4, \lambda'_6, \dots$ whose polarization plane is rotated by 90° upon

reflection from non-linear interferometer 110, is transformed to p-polarization with respect to second PBS 104 and therefore passes straight through the second PBS 104 towards and through the reciprocal optical rotator 108 and the non-reciprocal optical rotator 106.

Because it passes through the elements 106-108 from right to left (Fig. 5b), the light comprising the even channels $\lambda'_2, \lambda'_4, \lambda'_6, \dots$ incurs a 90° rotation of the plane of its polarization and thus is transformed to s-polarized light with respect to the first PBS 102. These even channels comprising s-polarized light are thus reflected by the first PBS 102 in the direction of optical reflector 112 and are then reflected by optical reflector 112 towards and into the port 116b.

Figures 5a-5b illustrate the paths of the channels $\lambda'_1-\lambda'_n$, originally input from port 116d, through the channel separator 500. Because the channel separator 500 comprises the same functionality as that of the channel separator 100 with respect to channels $\lambda_1-\lambda_n$ input to the channel separator 100 from port 116a, Figs. 1a-1c essentially illustrate the paths of the channels $\lambda_1-\lambda_n$ through either the channel separator 100 or the channel separator 500. By comparing Figs. 1b-1c with Figs. 5a-5b, it is seen that the first output port 116b receives the odd channels from the set $\lambda_1-\lambda_n$ together with the even channels from the set $\lambda'_1-\lambda'_n$ and that the second output port 116c receives the even channels from the set $\lambda_1-\lambda_n$ together with the odd channels from the set $\lambda'_1-\lambda'_n$.

Figure 5c illustrates the pathways of inadvertently reflected signal light rays through the sixth preferred embodiment of the multi-functional separator in accordance with the present invention. Because the channel separator 500 comprises the same optical isolator components and functionality as the channel separator 200, the pathways of such inadvertently reflected channels are essentially identical to those within the separator 200 as

shown in Figs. 2a-2b and are not re-described. These channel pathways direct light that is inadvertently input to the channel separator 500 from either of the output ports 116b-116c away from either of the input ports 116a and 116d.

Figures 6a-6e illustrate a seventh preferred embodiment of a multi-functional separator in accordance with the present invention. The seventh preferred embodiment provides a 1x2 dense wavelength division de-multiplexer, an optical comb filter and an optical isolator. In the channel separator 600, the input port 116a, the two output ports 116b-116c, the first PBS 102, the second PBS 104, the non-linear interferometer 110, the non-reciprocal optical rotator 106, the reciprocal optical rotator 108, the non-reciprocal optical rotator 202 and the reciprocal optical rotator 204 are common to the similarly numbered components comprising the channel separator 200 (Figs. 2a-2b). However, in the channel separator 600, the first and second optical reflectors 112-114 of channel separator 200 are replaced by a third PBS 602 and a fourth PBS 604, respectively. Additionally, a second non-linear interferometer 606 and a third non-linear interferometer 608 are respectively disposed adjacent to the third PBS 602 at a side opposite to the port 116b and adjacent to the fourth PBS 604 at a side opposite to the port 116c.

As will be described in more detail following, the channel separator 600 comprises the same channel separation and optical isolation functionalities as the channel separator 200 and further comprises an optical comb filtering functionality. The channel separation functionality performed by the components common to the separator 200 comprises a first channel separation stage and the comb filtering functionality comprises a second filtering stage sequentially cascaded with the first stage.

Figure 6f shows a schematic representation of optical channels as they are transmitted through the channel separator stage supplemented by the channel comb filter stage of the seventh preferred embodiment of the multi-functional separator in accordance with the present invention. The channel separator stage 601 initially separates an initial optical input signal 603, comprised of a plurality of optical channels, into two signals each comprising a subset of the channels—a first signal subset 605 comprised primarily of “odd” channels and a second subset 607 comprised primarily of “even” channels, respectively. Histograms attached to each signal and signal subset represent, hypothetically, the intensities of the channels comprising each such signal. If the channel separator 601 is perfect then the signal 605 is comprised only of odd channels and the signal 607 is comprised only of even channels. However, since, in general, the separator 601 is not perfect, there is some “leakage” of even channels into signal 605 and of some odd channels into signal 607.

As shown in Fig. 6f, to increase the degree of isolation of the odd channel signal 605 from the even channels and of the even channel signal 607 from the odd channels, two optical channel comb filters, 609A and 609B, respectively, are incorporated into the apparatus. The first optical channel comb filter 609A (second optical channel comb filter 609B) is designed so as to transmit a high proportion of the intensity of the odd (even) channels and a negligible proportion of the intensity of the even (odd) channels. Taken together, the channel separator and each of the dense optical channel comb filters provides an acceptable level of isolation of the resulting odd channel and even channel signals, 611 and 613, respectively.

Returning to Fig. 6a, this drawing shows the pathways and polarization states of channels input to the channel separator 600 between the input port 116a and the non-linear

interferometer 110. This portion of the pathway of each channel through the channel separator 600 is referred to herein as the forward pathway. These forward pathways illustrated in Fig. 6a are identical to those shown for the channel separator 100 in Fig. 1a and are not re-described.

5 Figure 6b illustrates the pathways of the set of odd channels $\lambda_1, \lambda_3, \lambda_5, \dots$ through the seventh preferred embodiment of the multi-functional separator in accordance with the present invention, after interacting with and being reflected by the non-linear interferometer 110. The odd channels are reflected from the non-linear interferometer without polarization plane rotation and therefore the light comprising these channels remains p-polarized with respect to the second PBS 104. If the non-linear interferometer 110 does not operate perfectly, however, then a small, unwanted proportion of the light comprising the even channels may also be reflected therefrom as similarly p-polarized light. This p-polarized light comprising the odd channels (and possibly a small proportion of the even channels) passes directly through PBS 104 towards and through the reciprocal optical rotator 108 and the non-reciprocal optical rotator 106. Upon passing through the pair of elements 106-108 from right to left as shown in Fig. 6b, the light comprising the odd channels (and possibly a small proportion of the even channels) experiences a 90° rotation of the orientation of its polarization plane and therefore is transformed to light of s-polarization with respect to the first PBS 102 and the third PBS 602. As shown in Fig. 6b, the PBS 102 reflects this s-polarized light towards the third PBS 602 and, subsequently, the third PBS 602 reflects this light towards the second non-linear interferometer 606.

Figure 6c illustrates the pathways of the set of even channels $\lambda_2, \lambda_4, \lambda_6, \dots$ through the seventh preferred embodiment of the multi-functional separator in accordance with the

present invention, after interacting with and being reflected by the non-linear interferometer 110. Upon reflection from the non-linear interferometer 110, the light of the even channels incurs a 90° rotation of its polarization plane. Therefore the light comprising these even channels becomes s-polarized with respect to the second PBS 104. If the non-linear interferometer 110 does not operate perfectly, however, then a small, unwanted proportion of the light comprising the odd channels may also be reflected therefrom as similarly s-polarized light. This s-polarized light comprising the even channels (and possibly a small proportion of the odd channels) is reflected by PBS 104 towards and through the non-reciprocal optical rotator 202 and the reciprocal optical rotator 204 to the fourth PBS 604. Upon passing through the pair of elements 202-204 from top to bottom as shown in Fig. 6c, this light does not incur polarization rotation and therefore remains s-polarized with respect to the fourth PBS 604. As shown in Fig. 6c, the fourth PBS 604 reflects this s-polarized light comprising the even channels (and possibly a small proportion of the odd channels) towards the third non-linear interferometer 608.

The interaction of optical signals with either the second non-linear interferometer 606 or the third non-linear interferometer 608 together with the subsequent signal pathways comprises the comb filter stage of operation of the separator/isolator/comb filter 600. The nominal pathway of the odd channels in the comb filter stage is illustrated in Fig. 6b. As shown in Fig. 6b, the odd channels are reflected by the third PBS 602 with s-polarization and are thence directed to and reflected by the second non-linear interferometer 606. The non-linear interferometer 606 is configured such that odd channels reflected therefrom incur a 90° rotation of their polarization plane orientation. Thus, the polarization of the light of the odd channels reflected from non-linear interferometer 606 is transformed to p-polarization

with respect to PBS 602. This p-polarized light comprising the odd channels $\lambda_1, \lambda_3, \lambda_5, \dots$ is thenceforth transmitted directly through PBS 602 towards and into the second port 116b.

Similarly, the nominal pathway of the even channels in the comb filter stage is illustrated in Fig. 6c. As shown in Fig. 6c, the even channels are reflected by the fourth PBS 604 with s-polarization and are thence directed to and reflected by the third non-linear interferometer 608. The non-linear interferometer 608 is configured such that even channels reflected therefrom incur a 90° rotation of their polarization plane orientation. Thus, the polarization of the light of the even channels reflected from non-linear interferometer 608 is transformed to p-polarization with respect to PBS 604. This p-polarized light comprising the even channels $\lambda_2, \lambda_4, \lambda_6, \dots$ is thenceforth transmitted directly through PBS 604 towards and into the third port 116c.

Figures 6d and 6e illustrate the pathways through the seventh preferred embodiment of the multi-functional separator in accordance with the present invention of inadvertently reflected signal light rays and of the small proportion of signal light rays misdirected in the first channel separation stage. Figure 6d shows the pathways for inadvertently reflected even channels and for mis-directed odd channels. The inadvertently reflected even channels are input to the channel separator 600 from the third port 116c and are directed towards and through the fourth PBS 604 as p-polarized light rays. Simultaneously, the small, unwanted proportion of odd channels that are mis-directed towards non-linear interferometer 608 in the first (separation) stage comprise s-polarized signal light rays. The p-polarized light rays comprising the even channels are reflected by non-linear interferometer 608 with a 90° -polarization rotation and the s-polarized light rays comprising the odd channels are reflected by non-linear interferometer 608 without polarization rotation. Therefore, both such sets of

light rays are reflected from non-linear interferometer 608 as s-polarized rays. The PBS 604 reflects these s-polarized rays towards and through the reciprocal optical rotator 204 and the non-reciprocal optical rotator 202. Upon passing through the pair of components 202-204 from bottom to top as illustrated in Fig. 6d, the polarization orientation of the reflected and mis-directed signal light rays is rotated by 90° so as to be transformed into p-polarization with respect to the second PBS 104. These p-polarized light rays, comprising unwanted reflected even channels and mis-directed odd channels, then pass directly through PBS 104 so as to exit the channel separator 600 without being directed towards any port.

Figure 6e shows signal light pathways through the comb filtering stage of apparatus 600 for inadvertently reflected odd channels and for mis-directed even channels. The inadvertently reflected odd channels are input to the channel separator 600 from the second port 116b and are directed towards and through the third PBS 602 as p-polarized light rays. Simultaneously, the small, unwanted proportion of even channels that are mis-directed towards non-linear interferometer 606 in the first (separation) stage comprise s-polarized signal light rays. The p-polarized light rays comprising the odd channels are reflected by non-linear interferometer 606 with a 90° -polarization rotation and the s-polarized light rays comprising the even channels are reflected by non-linear interferometer 608 without polarization rotation. Therefore, both such sets of light rays are reflected from non-linear interferometer 606 as s-polarized rays. The PBS 602 reflects these s-polarized rays towards the first PBS 102 which again reflects them towards and through the non-reciprocal optical rotator 106 and the reciprocal optical rotator 108. Upon passing through the pair of components 106-108 from left to right as illustrated in Fig. 6e, the polarization orientation of the reflected and mis-directed signal light rays remains s-polarized with respect to the second

PBS 104. These s-polarized light rays, comprising unwanted reflected odd channels and mis-directed even channels, are then reflected by PBS 104 so as to exit the apparatus 600 without being directed towards any port.

Figure 6g illustrates a side view of an eighth preferred embodiment of a multi-functional separator in accordance with the present invention. The eighth preferred embodiment provides a 1×2 dense wavelength division de-multiplexer, an optical comb filter and optical isolator. The channel separator 650 (Fig. 6g) is constructed and operates similarly to the channel separator 600 (Figs. 6a-6e) except that the PBS 604 is rotated about a vertical axis and the locations of the non-linear interferometer 608 and the output port 116c are reversed with respect to the PBS 604. Other aspects of the operation of channel separator 650 are similar to those of channel separator 600 and are not repeated. Many other similar modifications, in which one or more components are simply inverted, rotated or interchanged, would be readily apparent to one of ordinary skill in the art. All such modifications to any of the described embodiments of the present invention are considered to be within the spirit and scope of the present invention.

Figure 6h illustrates a side view of a ninth preferred embodiment of a multi-functional separator in accordance with the present invention. The ninth preferred embodiment provides a 1×2 dense wavelength division de-multiplexer, an optical comb filter and optical isolator. The channel separator 660 (Fig. 6h) is constructed similarly to the channel separator 650 (Fig. 6g) except that the first 110, second 606 and third 608 non-linear interferometers are all replaced by a single elongated non-linear interferometer 670 and an additional non-reciprocal optical rotator 616 and an additional reciprocal optical rotator 618 are disposed between the third PBS 602 and the non-linear interferometer 670. The optical

rotators 616-618 are configured such that the polarization plane of linearly polarized light passing through both rotators from left to right is not rotated whilst that of linearly polarized light passing therethrough from right to left incurs a 90° rotation. Alternatively, instead of providing the optical rotators 616-618, the optical rotators 106-108 could be elongated so as to cover the space adjacent to the third PBS 602. By tracing through the pathways and polarization orientations of signal light rays through the channel separator 660 in Fig. 6h, it may be verified that the channel separator 660 operates as a wavelength division de-multiplexer, an optical comb filter and an optical isolator.

Figures 7a-7e illustrate a tenth preferred embodiment of a multi-functional separator in accordance with the present invention. The tenth preferred embodiment provides a 1×4 dense wavelength division de-multiplexer. In the channel separator 700 (Fig. 7a), an input set of wavelength division multiplexed channels λ_1 - λ_n is divided into two channel subsets in a first internal channel separation stage and each such subset is further divided into two smaller subsets in a subsequent second stage. Each of the four channel subsets resulting from the sequentially arranged two divisions is then output to a different respective output port.

In the channel separator 700 (Fig. 7a), the three ports 116a-116c, the first PBS 102, the second PBS 104, the third PBS 602, the fourth PBS 604, the first non-linear interferometer 110, the first non-reciprocal optical rotator 106 and the first reciprocal optical rotator 108 are common to and are disposed similarly to the respective similarly numbered components comprising the channel separator 600 (Fig. 6a). The common components comprise the first separation stage components of channel separator 700. Further, the channel separator 700 (Fig. 7a) comprises an additional two output ports 116d-116e, a

second non-linear interferometer 706, a third non-linear interferometer 708, a fifth PBS 702, a sixth PBS 710, a first optical reflector 704, a second optical reflector 712, a second non-reciprocal optical rotator 714, a second reciprocal optical rotator 716, a third non-reciprocal optical rotator 718, and a third reciprocal optical rotator 720. These additional components are disposed within the channel separator 700 as illustrated in Figs. 7a-7e.

In the channel separator 700, each of the second 706 and third 708 non-linear interferometers comprises a periodicity—that is, a wavelength difference at which the properties of light reflected from the interferometer are repeated—that is double that of first non-linear interferometer 110. The second 706 and the third 708 non-linear interferometers that comprise channel separator 700 are disposed similarly to the non-linear interferometers 606-608 of channel separator 600 with respect to the common first-separation-stage components.

Also, in the channel separator 700, the fifth PBS 702 is interposed between the third PBS 602 and the second non-linear interferometer 706 whilst the second non-reciprocal optical rotator 714 and the second reciprocal optical rotator 716 are optically coupled to and interposed between the PBS 602 and the PBS 702. Likewise, the sixth PBS 710 is interposed between the fourth PBS 604 and the third non-linear interferometer 708 whilst the third non-reciprocal optical rotator 718 and the third reciprocal optical rotator 720 are optically coupled to and interposed between the PBS 604 and the PBS 710. The first optical reflector 704 is disposed so as to receive light reflected by fifth PBS 702 and reflect it towards the fourth port 116d. The second optical reflector 712 is disposed so as to receive light reflected by sixth PBS 710 and reflect it towards the fifth port 116e.

and Fig. 7c, the p-polarized odd channels thence pass straight through the PBS 702 so as to interact with and be reflected by the second non-linear interferometer 706.

The non-linear interferometer 706 has the property of reflecting the linearly polarized light of the odd channels input thereto such that the first set of odd channels $\lambda_1, \lambda_5, \lambda_9, \dots$ is reflected without polarization plane rotation (Fig. 7b) whilst the second set of odd channels $\lambda_3, \lambda_7, \lambda_{11}, \dots$ is reflected with a 90° polarization-plane rotation (Fig. 7c). Therefore, upon reflection from non-linear interferometer 706, the first set $\lambda_1, \lambda_5, \lambda_9, \dots$ of odd channels remains p-polarized with respect to PBS 702 and passes straight through PBS 702 towards and through the second non-reciprocal optical rotator 714 and the second reciprocal optical rotator 716 (Fig. 7b) whilst the second set $\lambda_3, \lambda_7, \lambda_{11}, \dots$ of odd channels is s-polarized with respect to PBS 702 and is reflected by PBS 702 towards the first optical reflector 704 (Fig. 7c). Because the first set of odd channels $\lambda_1, \lambda_5, \lambda_9, \dots$ passes through the pair of rotators 714-716 from right to left, the light of these channels remains p-polarized with respect to PBS 602 and therefore passes straight through PBS 602 towards and into the second port 116b (Fig. 7b). The second set of odd channels $\lambda_3, \lambda_7, \lambda_{11}, \dots$ is reflected by reflector 704 towards and into the fourth port 116d (Fig. 7c). In this fashion, the outputs of the first and second sets of odd channels are separated from one another as well as from those of the even channels.

Figures 7d-7e illustrate the pathways of the even channels $\lambda_2, \lambda_4, \lambda_6, \dots$ through the tenth preferred embodiment of a multi-functional separator in accordance with the present invention, after interaction with and reflection by the first non-linear interferometer 110. Figures 7d-7e also illustrate the subsequent division of the even channels into a first subset $\lambda_2, \lambda_6, \lambda_{10}, \dots$ of the even channels and a second subset $\lambda_4, \lambda_8, \lambda_{12}, \dots$ of the even channels,

respectively. The pathways of the even channels from the first non-linear interferometer 110 to the fourth PBS 604 comprise a portion of the first channel separation stage and are similar to those illustrated for separator 600 in Fig. 6c. These pathways are therefore not re-described. After reflection from the fourth PBS 604 (Figs. 7d-7e), the s-polarized light of the odd channels is directed towards and through the third reciprocal optical rotator 720 and the third non-reciprocal optical rotator 718 and thence to the sixth PBS 710. Because the light passes through the pair of rotators 718-720 from right to left, the polarization of this light is rotated by 90° so as to be transformed to p-polarized light with respect to the sixth PBS 710. As shown in both Fig. 7d and Fig. 7e, the p-polarized even channels thence pass straight through the PBS 710 so as to interact with and be reflected by the third non-linear interferometer 708.

The non-linear interferometer 708 has the property of reflecting the linearly polarized light of the even channels input thereto such that the first set of even channels $\lambda_2, \lambda_6, \lambda_{10}, \dots$ is reflected without polarization plane rotation (Fig. 7d) whilst the second set of even channels $\lambda_4, \lambda_8, \lambda_{12}, \dots$ is reflected with a 90° polarization-plane rotation (Fig. 7e).

Therefore, upon reflection from non-linear interferometer 708, the first set $\lambda_2, \lambda_6, \lambda_{10}, \dots$ of even channels remains p-polarized with respect to PBS 710 and passes straight through PBS 710 towards and through the third non-reciprocal optical rotator 718 and the third reciprocal optical rotator 720 (Fig. 7d) whilst the second set $\lambda_4, \lambda_8, \lambda_{12}, \dots$ of even channels is s-polarized with respect to PBS 710 and is reflected by PBS 710 towards the second reflector 712 (Fig. 7e). Because the first set of even channels $\lambda_2, \lambda_6, \lambda_{10}, \dots$ passes through the pair of rotators 718-720 from left to right, the light of these channels remains p-polarized with respect to PBS 604 and therefore passes straight through PBS 604 towards and into the third

port 116c (Fig. 7d). The second set of even channels $\lambda_4, \lambda_8, \lambda_{12}, \dots$ is reflected by reflector 712 towards and into the fifth port 116e (Fig. 7e). In this fashion, the outputs of the first and second sets of even channels are separated from one another as well as from those of the odd channels. From the foregoing discussions, it is apparent that the separator 700 receives, from a first port, a wavelength division multiplexed light comprised of a plurality of n channels λ_1 - λ_n and separates the plurality into four subsets of channels, each of which subsets are output from a respective one of a set of four output ports. In this fashion, the separator 700 functions as a 1x4 de-multiplexer.

Figure 7f presents a side view of an eleventh preferred embodiment of a multi-functional separator in accordance with the present invention. The eleventh preferred embodiment also provides a 1x4 dense wavelength division de-multiplexer. The separator 750 (Fig. 7f) comprises identical functionality to and many of the same components as the separator 700 (Figs. 7a-7e) except that the six polarization beam splitters 102, 104, 602, 604, 702, 710 and the two optical reflectors 704, 712 are all replaced by a set of prisms. The prisms within the separator 750 comprise two larger right-angle prisms 752a-752b, a pair of smaller right-angle prisms 754a-754b, and four rhomboid prisms 756a-756d, all disposed as shown in Fig. 7f. The “slanted” surfaces of the prisms are configured so as to reflect s-polarized light and transmit p-polarized light as previously indicated for polarization beam splitters in other embodiments of the present invention. Thus, the separator 750 operates similarly to the separator 700.

Figure 8 illustrates a twelfth preferred embodiment of a multi-functional separator in accordance with the present invention. The twelfth preferred embodiment provides a 4x1 dense wavelength division multiplexer. The 4x1 multiplexer 800 (Fig. 8) is identical in

construction to the 1×4 de-multiplexer 700 (Figs. 7a-7e) except that, as previously described in reference to the multiplexer 400, each adjacent pair of optical rotators functions in the reverse sense from the corresponding pair of rotators in the de-multiplexer 700. Therefore, in the multiplexer 800 (Fig. 8), the pathways of signal light rays are exactly reversed from those in the de-multiplexer 700 (Figs. 7a-7e). As shown in Fig. 8, in the multiplexer 800, the channels $\lambda_1, \lambda_5, \lambda_9, \dots$ input from port 116b are combined together with the channels $\lambda_2, \lambda_6, \lambda_{10}, \dots$ input from port 116c, the channels $\lambda_3, \lambda_7, \lambda_{11}, \dots$ input from port 116d and the channels $\lambda_4, \lambda_8, \lambda_{12}, \dots$ input from port 116e such that the combined channels λ_1 - λ_n are all output from the port 116a.

The remaining discussion is now directed to Figs. 9A-11 which represent the construction and functioning of interleaved Optical Add/Drop Multiplexers (interleaved OADM's) in accordance with the present invention. Figure 11 is a schematic routing diagram of channels through an interleaved OADM in accordance with the present invention. Such an interleaved OADM receives input from both an Input Port 116a and an Add Port 116d and directs channels to both an Output Port 116c and a Drop Port 116b. It is assumed that, in the operation of the interleaved OADM, the n channels λ_1 - λ_n are received from the Input Port 116a but that only the odd channels $\lambda'_1, \lambda'_3, \lambda'_5, \dots$ are received from the Add Port 116d. It is understood that the channel λ'_1 comprises the same band of physical wavelengths as the channel λ_1 but carries a different signal from the channel λ_1 and that similar statements hold true for the remaining odd channels λ'_3 and λ_3 , etc. The channels $\lambda_1, \lambda_3, \lambda_5, \dots$ are dropped—that is, output to the Drop Port 116b—and replaced by the channels $\lambda'_1, \lambda'_3, \lambda'_5, \dots$ in the composite optical signal output to the Output Port 116c.

Alternatively, the even channels $\lambda'_2, \lambda'_4, \lambda'_6, \dots$ could be received from the Add Port 116d whilst the even channels $\lambda_2, \lambda_4, \lambda_6, \dots$ are dropped.

As shown schematically in Fig. 11, an interleaved OADM in accordance with the present invention retains the basic function of a 1x2 channel separator described previously in this specification. The basic function comprises the separation of the channels λ_1 - λ_n into a set of odd channels $\lambda_1, \lambda_3, \lambda_5, \dots$ that are output to a first port (the Drop Port 116b) and into a set of even channels $\lambda_2, \lambda_4, \lambda_6, \dots$ that are output to a second port (the Output Port 116c). In addition, an interleaved OADM in accordance with the present invention provides the functions of receiving the channels $\lambda'_1, \lambda'_3, \lambda'_5, \dots$ from the Add Port 116d and multiplexing these channels together with the even channels $\lambda_2, \lambda_4, \lambda_6, \dots$ and outputting these combined channels together at the Output Port 116c. There is no optical pathway or connection between the Add Port 116b and the Drop Port 116d.

Figures 9A-9E each provide a side view of a first preferred embodiment of an interleaved Optical Add/Drop Multiplexer (interleaved OADM) in accordance with an embodiment in accordance with the present invention. The interleaved OADM 900 (Figs. 9A-9E) comprises several components in common with the channel separator 500 (Figs. 5a-5c). Such common components include the port 116a, the first PBS 102 optically coupled to the port 116a, the second PBS 104, the third PBS 502, the first non-reciprocal optical rotator 106 and first reciprocal optical rotator 108 optically coupled between the first PBS 102 and the second PBS 104, the second non-reciprocal optical rotator 202 and second reciprocal optical rotator 204 optically coupled between the second PBS 104 and the third PBS 502 and the non-linear interferometer 110 optically coupled to the second PBS 104. As is also the case within the channel separator 500, the first PBS 102, first non-reciprocal optical rotator

106, first reciprocal optical rotator 108 and second PBS 104 are disposed along a first axis; and the second PBS 104, second non-reciprocal optical rotator 202, second reciprocal optical rotator 204 and the third PBS 502 are disposed along a second axis that is not parallel to the first axis.

5 The interleaved OADM 900 further comprises a second port 116b and a second non-linear interferometer 606 optically coupled to the first PBS 102, wherein the first PBS 102, second port 116b and second non-linear interferometer 606 are disposed along a third axis not parallel to the first axis; a third port 116c optically coupled to the second PBS 104 along the first axis, a third non-linear interferometer 608 optically coupled to the third PBS 502 along the second axis, and a fourth port 116d, not along the second axis, optically coupled to the third PBS 502. The pair of optical rotators 106-108 are configured within the interleaved OADM 900 such that linearly polarized light passing completely therethrough from left to right (as drawn) incurs a 90°-polarization plane rotation whilst light passing completely therethrough from right to left incurs no polarization plane rotation. The pair of optical
15 rotators 202-204 are configured within the interleaved OADM 900 such that linearly polarized light passing completely therethrough from top to bottom (as drawn) incurs a 90°-polarization plane rotation whilst light passing completely therethrough from bottom to top incurs no polarization plane rotation.

20 Preferably, each of the non-linear interferometers 110, 606 and 608 comprises an apparatus as disclosed in the above-referenced U.S. Patents 6,169,604 and 6,310, 690. Each of these non-linear interferometers has the property of reflecting all linearly polarized light input thereto such that reflected light comprising a first set of channels (e.g., the "odd" channels) that is interleaved with a second set of channels is reflected without any

polarization plane rotation whereas the reflected light comprising the second set of channels (e.g., the "even" channels) is reflected with a 90° polarization plane rotation. The band widths of first set and the second set of channels need not be the same. These non-linear interferometers are also referred to herein as either "reflective non-linear interferometers" or "reflection interferometers" because substantially all light input to such an interferometer is completely reflected. It will be readily recognized that reflection interferometers comprising the same polarization rotation properties just described are functionally equivalent within this invention.

Within the interleaved OADM 900, the first port 116a comprises the Input Port, the third port 116c comprises the Output Port, the fourth port 116d comprises the Add Port and the second port 116b comprises the Drop Port. All four ports 116a-116d are polarizing ports of the type shown in Fig. 1d. Figure 9A shows the forward pathways—that is the pathways up to the first non-linear interferometer 110—of signal light rays of channels λ_1 - λ_n through the interleaved OADM 900 from the Input Port 116a to the non-linear interferometer 110.

The collimated light input from the port 116a is p-polarized with respect to the first PBS 102 and passes straight through the first PBS 102 without deflection or reflection to the pair of optical rotators 106-108. Upon passing through the pair of optical rotators 106-108, the polarization of the light comprising the channels λ_1 - λ_n is rotated by 90° such that this light becomes s-polarized with respect to the second PBS 104. The light of the channels λ_1 - λ_n is thus reflected by the second PBS 104 to the first non-linear interferometer 110.

Figure 9B shows the return pathways—that is the pathways from the first non-linear interferometer 110 to a port—through the interleaved OADM 900. The pathway of odd channels $\lambda_1, \lambda_3, \lambda_5, \dots$ from the first non-linear interferometer 110 to the Drop Port 116b and

of even channels $\lambda_2, \lambda_4, \lambda_6, \dots$ from the first non-linear interferometer 110 to the Output Port 116c are both illustrated in Fig. 9B. Upon reflection from the first non-linear interferometer 110, the polarization of light comprising the even channels is rotated by 90° whilst the polarization of the odd channels remains unchanged. Both sets of channels are reflected from the first non-linear interferometer 110 to the second PBS 104 but are separated thereat because the odd channels are s-polarized and the even channels are p-polarized with respect to the second PBS 104. The odd channels are thus deflected towards and through the pair of optical rotators 106-108 whilst the even channels are directed towards and through the pair of optical rotators 202-204.

Both the set of odd channels and the set of even channels maintain their respective polarization upon passing from right-to-left through the optical rotators 106-108 to the first PBS 102 and upon passing from bottom-to-top through the optical rotators 202-204 to the third PBS 502. Therefore, the odd channels remain s-polarized with respect to the first PBS 102 and the even channels remain p-polarized with respect to the third PBS 502. The s-polarized odd channels are reflected or deflected by the first PBS 102 to the second non-linear interferometer 606 and the p-polarized even channels are transmitted through the third PBS 502 to the third non-linear interferometer 608.

Both the second non-linear interferometer 606 and the third non-linear interferometer 608 comprising the apparatus 900 are adjusted or configured to as to rotate the polarization of light of the odd channels while leaving the polarization of light of the even channels unchanged. Consequently, upon reflection from the second non-linear interferometer 606, the polarization of the light of the odd channels is rotated so as to become p-polarized with respect to the first PBS 102 and, upon reflection from the third non-linear interferometer

608, the polarization of the light of the even channels remains p-polarized with respect to the third PBS 502. The odd channels then pass through the first PBS 102 undeflected so as to be output at the port 116b. The even channels pass undeflected once again through the third PBS 502 so as to pass through the optical rotators 202-204 from top-to-bottom to the second PBS 104. The polarization plane of the light of the even channels is rotated by the optical rotators 202-204 so as to become s-polarized with respect to the second PBS 104. The even channels are thus deflected or reflected by the second PBS 104 so as to be output at the port 116c.

Figure 9C illustrates the pathways of the added channels $\lambda'_1, \lambda'_3, \lambda'_5, \dots$ through the interleaved OADM 900. The collimated light of the channels $\lambda'_1, \lambda'_3, \lambda'_5, \dots$ is input from the port 116d and directed to the third PBS 502 with a polarization that comprises s-polarization with respect to the third PBS 502. These added channels comprising s-polarized light are thus reflected or deflected by the third PBS 502 to the third non-linear interferometer 608. Since the added channels $\lambda'_1, \lambda'_3, \lambda'_5, \dots$ comprise wavelengths corresponding to "odd" channels, the polarization plane of the light comprising the added channels is rotated by 90° upon reflection from the third non-linear interferometer 608 back to the third PBS 502. Therefore, this reflected light is p-polarized with respect to the third PBS 502 and passes undeflected through the third PBS 502 towards and through the pair of optical rotators 202-204. Because it passes through the pair of optical rotators 202-204 from top-to-bottom, the polarization of the light comprising the odd channels is rotated by 90° upon passing therethrough so as to become s-polarized with respect to the second PBS 104. The added channels are thus deflected or reflected by the second PBS 104 so as to be output at the port 116c.

From the above discussion of the operation of the interleaved OADM 900, it may be noted that the set of odd channels $\lambda_1, \lambda_3, \lambda_5, \dots$ and the set of even channels $\lambda_2, \lambda_4, \lambda_6, \dots$ each encounters two non-linear interferometers. The odd channels interact with both the first non-linear interferometer 110 and the second non-linear interferometer 606 whereas the even channels interact with both the first non-linear interferometer 110 and the third non-linear interferometer 608. Because of these dual interactions, the interleaved OADM 900 comprises combined channel separation and comb filtering properties of the type schematically illustrated by Fig. 6f. Stated in another fashion, any channels that may be misdirected after interaction with the first non-linear interferometer 110 are further filtered by interaction with another non-linear interferometer so as to be prevented from entering the incorrect one of the two ports 116b-116c.

Figures 9D-9E illustrate the pathways of misdirected even channels and misdirected odd channels after interaction with the second non-linear interferometer 606 and the third non-linear interferometer 608, respectively. These channels might be misdirected to these locations, for instance, through imperfect operation of the first non-linear interferometer 110, which would result in incomplete separation of the odd and even channels by the second PBS 104. Both the second non-linear interferometer 606 and the third non-linear interferometer 608 are adjusted or configured within the apparatus 900 to as to rotate the polarization of light of the odd channels while leaving the polarization of light of the even channels unchanged.

As a result of the above property, upon reflection from the second non-linear interferometer 606 back to the first PBS 102 (Fig. 9D), the polarization of the light of the misdirected even channels remains s-polarized with respect to the first PBS 102 and is

reflected or deflected thereat back through the optical rotators 106-108 to the second PBS 104. Upon passing from left-to-right through the optical rotators 106-108, the polarization of the light of the misdirected even channels is rotated by 90° so as to become p-polarized with respect to the second PBS 104. These misdirected channels then pass undeflected through the second PBS 104 in the direction of port 116c. However, the port 116c cannot accept these channels since only light polarized perpendicularly to the plane of the drawing can enter this port.

Upon reflection from the third non-linear interferometer 608 back to the third PBS 502 (Fig. 9E), the polarization of the light of the misdirected odd channels becomes s-polarized with respect to the third PBS 502 and is reflected or deflected thereat in the direction of the port 116d. This misdirected odd-channel light may thus enter the port 116d. However, since the port 116d is an input port with respect to the interleaved OADM 900, the entry of the misdirected odd-channel light into this port will not have any adverse consequences provided that a separate optical isolator (not shown) is disposed somewhere within the external optical path leading to the port 116d.

Figures 10A-10B show a second and a third preferred embodiment, respectively, of an interleaved OADM in accordance with the present invention. The second preferred embodiment of the interleaved OADM 950 illustrated in Fig. 10A is similar to the interleaved OADM 900 (Figs. 9A-9E) except that the second non-linear interferometer 606 is adjusted or configured so as to rotate the polarization only of light of even channels (in similar fashion to the first non-linear interferometer 110) and, accordingly, a third non-reciprocal optical rotator 616 and a third reciprocal optical rotator 618 are optically coupled between the first PBS 102 and the second non-linear interferometer 606. The third preferred

embodiment of the OADM 970 illustrated in Fig. 10B is similar to the OADM 950 (Fig. 10A) except that the third non-linear interferometer 608 is also adjusted or configured so as to rotate the polarization only of light of even channels and, accordingly, a fourth non-reciprocal optical rotator 906 and a fourth reciprocal optical rotator 908 are optically coupled between the third PBS 502 and the third non-linear interferometer 608.

Both the pair of rotators 616-618 and the pair of rotators 906-908 rotate the plane of only linearly polarized light passing completely therethrough in a certain direction—either top-to-bottom or bottom-to-top—and do not rotate the polarization plane of linearly polarized light passing therethrough in the opposite direction. Within the apparatus 950 (Fig. 10A), the operation of the second non-linear interferometer 606 is configured oppositely to its respective configuration within the apparatus 900. Within the apparatus 970 (Fig. 10B), both the operation of the second and third non-linear interferometers 606-608 are configured oppositely to their respective configuration within the apparatus 900. Because of these configurations, the combined polarization rotation effects imparted by a non-linear interferometer—either the non-linear interferometer 606 or the non-linear interferometer 608—and the adjacent pair of optical rotators are the same as those imparted by the non-linear interferometer alone within the apparatus 900. Therefore, the pathways of channels are unchanged from those already described within the apparatus 900.

A multi-functional channel separator and channel combiner has been disclosed. The channel separator in accordance with the present invention is capable of functioning as a dense wavelength division demultiplexer or multiplexer. In the preferred embodiment, the channel separator comprises a polarizing input port, two polarizing output ports, a reflective non-linear interferometer, a pair of polarization beam splitters, and a non-reciprocal optical

rotator and a reciprocal optical rotator, wherein the two optical rotators are disposed adjacent to one another and interposed between the two polarization beam splitters. Each of the polarizing input and polarizing output ports comprises an optical fiber, a collimator, a birefringent walk-off plate and a non-reciprocal optical rotator. The channel separator is easily aligned by adjusting the positions of each of the polarizing input and output ports. Further embodiments of the present invention provide additional optical isolation, optical circulation, optical comb filtering and/or two-stage channel separation capabilities.

Although the present invention has been described in accordance with the embodiments shown, one of ordinary skill in the art will readily recognize that there could be variations to the embodiments and those variations would be within the spirit and scope of the present invention. Accordingly, many modifications may be made by one of ordinary skill in the art without departing from the spirit and scope of the appended claims.